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Measurement of the moments of the hadronic invariant mass distribution in semileptonic B decays

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Using 180 pb^{-1} of data collected with the CDF II detector in Run II of the Tevatron, we measure the first two moments of the invariant mass-squared distribution of the charm-hadron system in semileptonic B decays. We measure directly the first two moments of the D^{**} component for a minimum lepton momentum in the B rest frame of 0.7 GeV/c to be $\langle m^2_{D^{**}}\rangle = (5.83 \pm 0.16_{\rm stat} \pm 0.08_{\rm syst})\,{\rm GeV}^2$, $\langle (m^2_{D^{**}} - \langle m^2_{D^{**}}\rangle)^2\rangle = (1.30 \pm 0.69_{\rm stat} \pm 0.20_{\rm syst})\,{\rm GeV}^4$. After combining them with the known contributions from D and D^* we find for the moments of the charm-hadron system $\langle M^2_{X_c}\rangle - m^2_{\overline{D}} = (0.459 \pm 0.037_{\rm stat} \pm 0.065_{\rm syst})\,{\rm GeV}^2$, $\langle (M^2_{X_c} - \langle M^2_{X_c}\rangle)^2\rangle = (1.04 \pm 0.25_{\rm stat} \pm 0.12_{\rm syst})\,{\rm GeV}^4$, where $m_{\overline{D}}$ is the spin-averaged D mass and the systematic error is dominated by the uncertainty in the branching ratios used in the combination of the D, D^* and D^{**} pieces. From the moments we determine the non-perturbative HQET parameters Λ and λ_1 in the pole and 1S mass schemes.

1. INTRODUCTION

Currently, the most precise method for determining $|V_{cb}|$ is based on the measurement of the inclusive semileptonic partial width of B mesons into charm, $\Gamma_{sl} = \Gamma(B \to X_c l \nu_l)$. The Operator Product Expansion (OPE) applied to Heavy Quark Effective Theory (HQET) relates the experimental determination of Γ_{sl} to $|V_{cb}|$ [1,2]. The relationship takes the form of an expansion in inverse powers of the B mass, m_B. At each order in the expansion, new free non-perturbative parameters enter: one (Λ) at order $1/m_B$, two (λ_1 and λ_2) at order $1/m_B^2$, six at order $1/m_B^3$, etc. In order to extract $|V_{cb}|$ from Γ_{sl} some external information on these parameters is needed.

The same theoretical framework that predicts the value of Γ_{sl} predicts the value of any weighted integral of the differential rate $d\Gamma_{sl}/ds_H$, provided the weight is a smooth function of $s_H \equiv M^2_{X_c}$. By using as weight functions $f_1 = (s_H - m^2_{\overline{D}})$ and $f_2 = (s_H - \langle s_H\rangle)^2$, with $m_{\overline{D}} = 0.25 m_D + 0.75 m_{D^*}$, the spin-averaged D mass, one can define the first two moments of the hadronic mass distribution:

$$M_1 = \int_{s_H^{min}}^{s_H^{max}} ds_H \left(s_H - m^2_{\overline{D}}\right) \frac{1}{\Gamma_{sl}}\frac{d\Gamma_{sl}}{ds_H}$$

$$M_2 = \int_{s_H^{min}}^{s_H^{max}} ds_H \left(s_H - \langle s_H\rangle\right)^2 \frac{1}{\Gamma_{sl}}\frac{d\Gamma_{sl}}{ds_H} , \quad (1)$$

which are simply the (shifted) mean and variance of the $M^2_{X_c}$ distribution in semileptonic charmed decays of B mesons. The moments are not sensitive to $|V_{cb}|$, but they are more sensitive to the non-perturbative parameters of HQET than Γ_{sl} itself is. Therefore, measuring the moments provides a useful constraint on $\Lambda, \lambda_1, \lambda_2$ that improves the overall precision on $|V_{cb}|$ as determined from Γ_{sl}. This is the purpose of this analysis.

The s_H distribution in $B^- \to X_c^0 l^- \bar{\nu}_l$ decays can be split into three contributions corresponding to $X_c^0 = D^0, D^{*0}$, and D^{**0}, where D^{**0} stands for any neutral charmed state, resonant or not, other than D^0, D^{*0}:

$$\frac{1}{\Gamma_{sl}}\frac{d\Gamma_{sl}}{ds_H} = \frac{\Gamma_0}{\Gamma_{sl}}\cdot\delta(s_H - m^2_{D^0}) + \frac{\Gamma_*}{\Gamma_{sl}}\cdot\delta(s_H - m^2_{D^{*0}}) + \left(1 - \frac{\Gamma_0}{\Gamma_{sl}} - \frac{\Gamma_*}{\Gamma_{sl}}\right)\cdot f^{**}(s_H) , \quad (2)$$

where Γ_{sl} is the inclusive B^- semileptonic width, Γ_0 and Γ_* are the exclusive B^- partial widths to $D^0 l^- \bar{\nu}_l$ and $D^{*0} l^- \bar{\nu}_l$ respectively, and $f^{**}(s_H)$ is the (normalized) hadronic invariant mass-squared distribution in the D^{**0} channel. We will take

Γ_{sl}, Γ_0, Γ_*, m_{D^0} and $m_{D^{*0}}$ from the Particle Data Group [3] and concentrate on measuring $f^{**}(s_H)$. In this way, we only have to measure the invariant mass distribution for the D^{**0} component without having to determine the D^0, D^{*0} components or the relative normalizations between those and the D^{**0} channel. The D^{**0} spectrum is not well known, and includes, at least, two narrow and two wide states, together with a possible non-resonant $D^{(*)}\pi$ contribution. Its measurement is the main task of this analysis.

Only $D^{(*)+}\pi^-$ decays (charge conjugated channels are implicitly included throughout the paper) are reconstructed. Channels with neutrals are included using isospin relationships. Feed-downs from one channel to another because of missing neutrals are subtracted statistically using the data themselves and isospin relations. It is assumed that the $D^{(*)}\pi l^-\overline{\nu_l}$ decays of B^- saturate the difference between its inclusive and exclusive (to D^0 and D^{*0}) semileptonic branching ratios.

2. DATA ANALYSIS

The analysis uses a data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV with an integrated luminosity of about 180 pb^{-1}, collected between February 2002 and August 2003 with the upgraded Collider Detector (CDF II) at the Fermilab Tevatron. $B \to D^{*+}\pi^- l^- X$ decays were recorded using a trigger that requires a lepton l (electron or muon) with transverse momentum $p_T \geq 4$ GeV/c, and a track with $p_T \geq 2$ GeV/c and an impact parameter with respect to the beamline in excess of 120 μm.

Well-reconstructed tracks are selected, and only those with $p_T \geq 0.4$ GeV/c and $|\eta| < 2$ are retained. $D^{*+}[\to D^0\pi_*^+]l^-$ and D^+l^- events are reconstructed in the following decay channels: $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$, $K^-\pi^+\pi^0$, $D^+ \to K^-\pi^+\pi^+$. Tracks with the appropriate charge combination are vertexed in three dimensions without any pointing or mass constraints. A loose cut ($> 10^{-6}$) is applied to the probability of the vertex fit, and the D vertex is required to be at least 200 μm away from the beam line. Suitable ranges are selected in the D^0 (1.84–1.89 GeV/c^2) and D^+ (1.84–1.89 GeV/c^2) mass distributions. For the D^{*+} channel, an additional charged track is searched for, such that the $M(D^0\pi_*^+) - M(D^0)$ mass difference lies between 0.142 and 0.147 MeV/c^2. The $D^0 \to K^-\pi^+\pi^0$ channel is reconstructed from the satellite peak in the $K^-\pi^+$ mass distribution (1.50–1.70 GeV/c^2). In this case the $M(D^0\pi_*^+) - M(D^0)$ mass difference is required to be between 0.142 and 0.155 MeV/c^2.

The $D^{(*)+}l^-$ vertex (the B vertex) is reconstructed in three dimensions, and an additional pion, π_{**}^-, is required, such that its trajectory is at most 2.5 standard deviations away from the B vertex, and at least three standard deviations away from the beam line. These cuts were optimized using a D^{**} Monte Carlo sample based on ISGW2 [4] and Goity-Roberts [5] for the signal, and wrong-sign $\pi_{**}^+ l^-$ combinations in data for the background. The measured mass distributions in the $D^{*+}\pi^-$ and $D^+\pi^-$ channels are shown in Figs. 1 and 2, respectively.

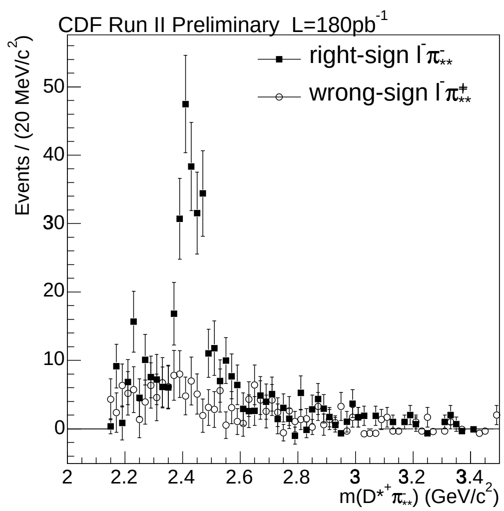

Figure 1. Raw invariant mass distribution for the $D^{*+}\pi_{**}^-$ channels. The mass region is limited at 3.5 GeV/c^2 for illustration.

Background subtraction is performed mostly using the data: side-bands are used to assess combinatorial background under the D^+ mass and $D^{*+} - D^0$ mass-difference peaks, and wrong-sign pion-lepton combinations to characterize the prompt background to the π_{**} candidates. The

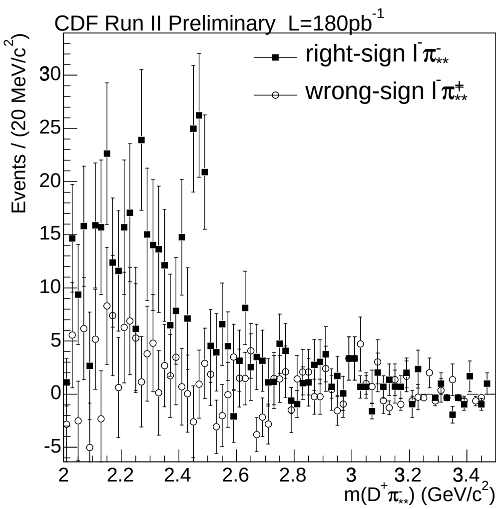

Figure 2. Raw invariant mass distribution for the $D^+\pi^-_{**}$ channel. The mass region is limited at 3.5 GeV/c^2 for illustration.

wrong-sign pion-lepton sample is subtracted from the right-sign sample, after performing side-band subtraction on both. A small (around 1% in rate) possible physics background, coming mostly from $B \to D_s^{(*)} D^{(*)}$ decays with the $D_s^{(*)}$ decaying semileptonically, is subtracted using Monte Carlo predictions.

Since only the shape of the mass distribution for the D^{**} component matters, the only efficiency corrections needed are those that can bias the mass distribution, along with the relative efficiency for the D^{*+} and D^+ components of the D^{**} piece. They are both obtained, as a function of the mass $M(D^{**})$, from a detailed, realistic Monte Carlo simulation after a small correction obtained using data. To be compared with theoretical predictions, the moments have to be measured with a well-defined cut on p_l^*, the lepton momentum in the B rest frame. Since we do not attempt to measure the boost of the B, we cannot access p_l^* directly in data. The mass-dependent efficiency corrections described above are used to correct our measurement to a value $p_l^* > 0.7$ GeV/c. We correct both for events with $p_l^* > 0.7$ GeV/c that do not pass our selection and for events with $p_l^* < 0.7$ GeV/c that do pass our selection. The value 0.7 GeV was chosen in order to minimize the correction. The correction itself depends on the detailed D^{**} mass spectrum in Monte Carlo. In order to assess the possible systematic error, the default B decay model, (based on ISGW2 [4] and Goity-Roberts [5]) has been replaced by a naive phase-space B semileptonic decay model and the differences in the ensuing correction factors as a function of $M(D^{**})$ considered as systematic errors. Furthermore, the corrections have also been computed for two alternative p_l^* cuts, 0.5 and 0.9 GeV/c. The moments obtained this way are different physical quantities and, hence, expected to be numerically different. However, if HQET describes the data, they should lead to compatible values of the HQET parameters. Differences between these have been considered as additional systematic uncertainties.

3. RESULTS

The corrected $D^{(*)+}\pi^-$ mass distribution (Fig. 3) is used to determine m_1 and m_2, the first and second moments of the D^{**} component of the mass-squared distribution, by simply computing the mean and variance of the corrected mass-squared distribution, without any assumption about the shape or rate of its several components: $m_1 \equiv \langle m^2_{D^{**}} \rangle = (5.83 \pm 0.16_{\rm stat} \pm 0.08_{\rm syst})$ GeV^2, $m_2 \equiv \langle (m^2_{D^{**}} - \langle m^2_{D^{**}} \rangle)^2 \rangle = (1.30 \pm 0.69_{\rm stat} \pm 0.20_{\rm syst})$ GeV^4, with a 61% positive correlation.

The full moments of the hadronic mass-squared distribution, M_1 and M_2, are obtained by combining m_1 and m_2 with the D and D^* pieces, computed using values from the Particle Data Group [3]. $M_1 \equiv \langle s_H \rangle - m^2_{\overline{D}} = (0.459 \pm 0.037_{\rm stat} \pm 0.019_{\rm exp} \pm 0.062_{\rm BR})$ GeV^2, $M_2 \equiv \langle (s_H - \langle s_H \rangle)^2 \rangle = (1.04 \pm 0.25_{\rm stat} \pm 0.07_{\rm exp} \pm 0.10_{\rm BR})$ GeV^4, where "BR" refers to the uncertainty coming from the branching ratios needed for the combination of the D, D^* and D^{**} pieces. There is a 69% positive correlation between M_1 and M_2.

Finally, the HQET parameters Λ and λ_1 are determined in the pole and 1S schemes using the predictions in [2], after applying constraints on the other HQET parameters coming from the known B and D hyperfine mass splittings: $\Lambda = (0.390 \pm 0.075_{\rm stat} \pm 0.026_{\rm exp} \pm 0.064_{\rm BR} \pm$

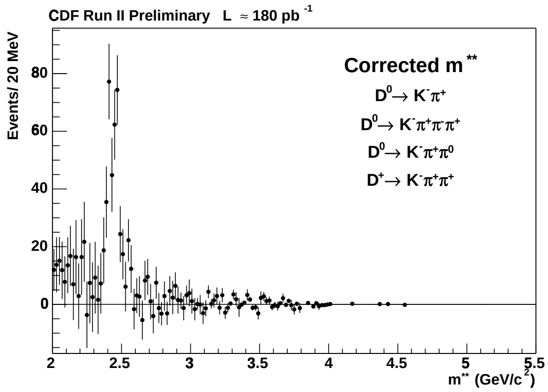

Figure 3. Fully corrected invariant mass distribution $m^{**} = M(D^{(*)+}\pi^-_{**})$. The number of events in each bin has been background subtracted and corrected for mass-dependent and D^*/D^+ relative efficiency corrections. The plotted errors take into account all corrections and subtractions.

$0.058_{\rm theo})$ GeV, $\lambda_1 = (-0.182 \pm 0.055_{\rm stat} \pm 0.016_{\rm exp} \pm 0.022_{\rm BR} \pm 0.077_{\rm theo})$ GeV^2, with a 79% negative correlation. Similarly, we extract the equivalent HQET parameters in the 1S scheme: $m_b^{1S} \equiv M_\Upsilon/2 - \Lambda^{1S} = (4.661 \pm 0.076_{\rm stat} \pm 0.026_{\rm exp} \pm 0.064_{\rm BR} \pm 0.089_{\rm theo})$ GeV, $\lambda_1^{1S} = (-0.276 \pm 0.047_{\rm stat} \pm 0.016_{\rm exp} \pm 0.022_{\rm BR} \pm 0.094_{\rm theo})$ GeV^2, with a 77% negative correlation.

Statistical errors dominate the measurements of m_1 and m_2; experimental systematic errors are all smaller. The main experimental systematics are summarized in the following: a correction for the ~ 60 MeV/c^2 mass resolution for the $K^-\pi^+\pi^0$ channel is either used or not and the difference is taken as a systematic error; the efficiency correction as a function of $M(D^{**})$ taken from data is either used or neglected; efficiency corrections from Monte Carlo are obtained either from a Monte Carlo sample based on a decay model according to ISGW2 and Goity-Roberts or based on a naive phase-space model, and we take the difference as a systematic uncertainty. Other experimental systematics include uncertainties on the level of the prompt background (studied with a fully reconstructed B sample) and uncertainties on B and D branching fractions used in the analysis. Uncertainties in the inclusive and exclusive semileptonic B branching ratios become important when combining m_1 and m_2 with the D^0 and D^{*0} pieces to obtain M_1 and M_2, the moments of the entire charm mass distribution. Finally, theoretical uncertainties become dominant in the extraction of the HQET parameters Λ and λ_1. The largest contribution to the theoretical systematic error is that estimated by varying the unknown third order HQET parameters in the ranges $2\rho_1 = ((0.5 \pm 0.5)\ \text{GeV})^3$, $T_i = ((0.0 \pm 0.5)\ \text{GeV})^3$.

4. SUMMARY

We have presented a measurement of the first two moments of the hadronic mass-squared distribution in semileptonic B decays to charm by combining our measurement of the $D^{(*)+}\pi^-$ mass spectrum above the D^{*0} mass with the known masses and branching ratios to $Dl\nu$ and $D^*l\nu$ taken from the Particle Data Group compilation [3]. These channels together are assumed to fully account for the inclusive semileptonic decay width of B mesons. The moments are then used to extract the two leading Heavy Quark Effective Theory parameters, Λ and λ_1, in both the pole mass and the 1S mass schemes. The results are in agreement with previous determinations at e^+e^- machines [6], and our precision in the moments is comparable or slightly better.

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